



KARSTIFICATION AND ITS INFLUENCE ON GROUNDWATER FLOW AND PERMEABILITY IN CARBONATE AQUIFERS: A LITERATURE REVIEW

KARSTIFIKASI DAN PENGARUHNYA TERHADAP ALIRAN AIR TANAH DAN PERMEABILITAS PADA AKUIFER KARBONAT: LITERATUR REVIEW

Isman Saleh

Halu Oleo University, Email: ismansaleh96@uho.ac.id

*email koresponden: ismansaleh96@uho.ac.id

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Abstract

Karstification is the dominant geological process controlling groundwater circulation and permeability in carbonate aquifers. Through the dissolution of carbonate rocks, karst processes create highly heterogeneous systems characterized by fractures, conduits, and interconnected channel networks that significantly influence groundwater flow dynamics. This literature review aims to synthesize current knowledge regarding the effects of karst on water circulation and permeability in carbonate aquifers based on hydrogeological, hydrochemical, geophysical, and numerical modeling studies from various regions worldwide. The review shows that karstification substantially enhances hydraulic conductivity and produces complex flow regimes ranging from diffuse fracture flow to turbulent conduit flow. The epikarst zone plays an important role in regulating infiltration and recharge distribution, while tectonic structures such as faults and fractures strongly control groundwater pathways and aquifer compartmentalization. Karst aquifers also exhibit strong spatial variability in permeability, making groundwater flow and contaminant transport difficult to predict using conventional hydrogeological approaches. In addition, the integration of equivalent porous medium (EPM), discrete fracture network (DFN), and conduit network (CN) models is essential for accurately representing karst aquifer behavior. Understanding the influence of karstification on groundwater circulation is therefore crucial for sustainable groundwater management and aquifer vulnerability assessment, particularly in regions facing increasing water demand and climate change pressures.

Keywords : Karstification, Carbonate Aquifer, Groundwater Circulation, Permeability, Hydrogeology.

Abstrak

Karstifikasi merupakan proses geologi utama yang mengontrol sirkulasi air tanah dan permeabilitas pada akuifer karbonat. Melalui pelarutan batuan karbonat, proses karst membentuk sistem yang sangat heterogen dengan keberadaan rekahan, saluran, dan jaringan conduit yang saling terhubung sehingga



memengaruhi dinamika aliran air tanah secara signifikan. Literature review ini bertujuan untuk mensintesis pengetahuan terkini mengenai pengaruh karst terhadap sirkulasi air dan permeabilitas pada akuifer karbonat berdasarkan studi hidrogeologi, hidrogeokimia, geofisika, dan pemodelan numerik dari berbagai wilayah di dunia. Hasil kajian menunjukkan bahwa karstifikasi secara signifikan meningkatkan konduktivitas hidraulik dan menghasilkan rezim aliran yang kompleks, mulai dari aliran difus melalui rekahan hingga aliran turbulen melalui conduit. Zona epikarst berperan penting dalam mengontrol infiltrasi dan distribusi imbuan air tanah, sementara struktur tektonik seperti sesar dan rekahan sangat memengaruhi jalur aliran air tanah dan kompartementalisasi akuifer. Akuifer karst juga menunjukkan variabilitas permeabilitas yang tinggi sehingga aliran air tanah dan transport kontaminan sulit diprediksi menggunakan pendekatan hidrogeologi konvensional. Selain itu, integrasi model equivalent porous medium (EPM), discrete fracture network (DFN), dan conduit network (CN) diperlukan untuk merepresentasikan perilaku akuifer karst secara lebih akurat. Pemahaman mengenai pengaruh karstifikasi terhadap sirkulasi air tanah sangat penting untuk mendukung pengelolaan sumber daya air tanah yang berkelanjutan dan penilaian kerentanan akuifer, khususnya pada wilayah yang menghadapi peningkatan kebutuhan air dan tekanan perubahan iklim.

Kata Kunci : Karstifikasi, Akuifer Karbonat, Sirkulasi Air Tanah, Permeabilitas, Hidrogeologi.

1. INTRODUCTION

Carbonate aquifers underlie approximately 15% of the Earth's land surface and supply drinking water to 20–25% of the global population (Fan et al., 2023; Medici & West, 2021). These aquifers are distinguished from other hydrogeological systems by the process of karstification—the dissolution of soluble carbonate rocks by circulating groundwater charged with CO₂—which fundamentally transforms their porosity, permeability, and flow dynamics. Karstification is a self-reinforcing process that occurs mainly along fractures and bedding planes in the shallow phreatic zone, leading to the formation of hierarchical channel networks embedded within a less karstified rock matrix (Worthington & Ford, 2009; Xanke et al., 2024). The resulting aquifers are characterized by extreme heterogeneity, anisotropy, and temporal variability in hydraulic properties, making them among the most challenging hydrogeological systems to characterize and model (Guardiola-Albert et al., 2014; Kuniansky et al., 2022; Tamburini & Menichetti, 2020).

The peculiarity of karst aquifers lies in the coexistence of multiple porosity types—matrix, fracture, and conduit—each contributing differently to groundwater storage and flow (Kilchmann et al., 2004; Kuniansky et al., 2022). While intergranular matrix porosity constitutes the largest volumetric proportion of water storage, flow is concentrated along solution-enlarged conduits characterized by high hydraulic conductivity (Kuniansky et al., 2022; Piccini et al., 2022). This triple-porosity structure produces hydraulic conductivities spanning up to eight orders of magnitude within a single aquifer system (Kuniansky et al., 2022), and groundwater velocities that often exceed 100 m/day through conduit networks (Worthington & Ford, 2009). The enormous heterogeneity poses significant challenges for water resource management, contaminant transport prediction, and aquifer vulnerability assessment (Medici et al., 2019; Medici & West, 2021).

Understanding how karst processes affect water circulation and permeability in carbonate aquifers is essential for sustainable groundwater management, particularly in regions facing water scarcity and climate change pressures (Filippini et al., 2018; Xanke et al., 2024). This literature review synthesizes current knowledge on the effects of karstification on groundwater circulation patterns and permeability distribution in carbonate aquifers, drawing on field studies, hydrogeophysical investigations, numerical modeling, and hydrochemical analyses from diverse geological settings worldwide.



2. RESEARCH METHOD

This review was conducted through a systematic synthesis of peer-reviewed journal articles, government reports, and book chapters addressing the hydrogeology of karst carbonate aquifers. The literature was sourced from studies spanning multiple geographic regions, including Europe (Italy, Spain, Croatia, UK, Germany, France, Poland), North America (USA, Canada), Asia (China, South Korea), and the Middle East. The selected references encompass a range of methodological approaches:

- a. Field-based hydrogeological investigations include spring monitoring and discharge analysis, piezometric measurements and pumping tests, tracer tests, and borehole geophysical logging. These methods provide direct observations of hydraulic parameters and flow behavior at various scales.
- b. Hydrochemical and isotopic approaches were employed to characterize groundwater flow paths, residence times, and water-rock interactions. Environmental tracers including stable isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$), tritium, CFCs, and major ion chemistry have been used to distinguish flow components and assess mixing processes in karst systems.
- c. Numerical modeling studies encompass equivalent porous medium (EPM), discrete fracture network (DFN), and conduit network (CN) approaches. These modeling frameworks represent different conceptualizations of karst aquifer heterogeneity and have been applied at scales ranging from individual sites to regional aquifer systems.
- d. Geophysical methods, including electrical resistivity tomography (ERT) and ambient seismic noise tomography, have been used to characterize subsurface heterogeneity, identify karstified zones, and delineate aquifer geometry.
- e. Laboratory and core-scale analyses provide fundamental data on matrix porosity and permeability relationships across different carbonate lithofacies. These data are essential for understanding the baseline hydraulic properties upon which karstification acts.

The review integrates findings across these methodological domains to construct a comprehensive understanding of how karst processes modify water circulation and permeability in carbonate aquifers, from the epikarst zone to deep phreatic systems.

3. RESULT AND DISCUSSION

Karstification and Permeability Enhancement

Karstification fundamentally transforms the permeability structure of carbonate aquifers through dissolution processes that enlarge pre-existing discontinuities into integrated channel networks. Laboratory experiments on dissolution rates of calcite and dolomite have established that a precipitous drop in dissolution rates occurs as chemical equilibrium is approached, and numerical models incorporating these kinetics demonstrate that dissolution occurs along the entire length of pathways through carbonate aquifers (Worthington & Ford, 2009). Over time, these pathways become enlarged and integrated, forming self-organized networks of channels with apertures typically in the millimeter to centimeter range (Worthington & Ford, 2009). This self-organization produces hierarchical drainage structures analogous to surface river networks, with the main conduit acting as a drain hydraulically connected to a diffusive pore network (Long & Putnam, 2009).

The degree of karstification is strongly controlled by lithology, with pure limestones being more susceptible to dissolution than dolostones (Kappel et al., 2020; Pavlić & Parlov, 2019). In the Dinaric karst of Croatia, limestones are deeply karstified and serve as the main carriers of groundwater toward large karst springs, while pure dolostones constitute less permeable carbonate rocks that decrease the overall permeability of the rock mass (Pavlić & Parlov, 2019). Similarly, in New York State, limestone formations develop karst features more readily than dolostones because dolostone, being calcium magnesium carbonate, has different mineral characteristics that make it less easily solutioned (Kappel et al., 2020). The solubility difference is significant: carbonate bedrock solubility is 0.39 g/L for dolostone versus 0.0062 g/L for limestone (Kappel et al., 2020).



Matrix permeability in carbonate rocks is generally very low, ranging from 10^{-18} to 10^{-13} m² (0.001 to 100 mD) depending on lithofacies (Bohnsack et al., 2020; Homuth et al., 2014). Bohnsack et al. (2020) found that permeability measured on core samples from the Upper Jurassic Malm reservoir in southern Germany was scattered over several orders of magnitude (10^{-4} to 10^2 mD), with dominant permeability trends mappable using facies-related models. However, fractured, karstified, and vuggy zones cannot be captured by matrix-scale models and result in underestimation of permeability at the reservoir scale (Bohnsack et al., 2020). Homuth et al. (2014) confirmed that matrix permeability has only a minor effect on reservoir sustainability except for some grainstones and dolomitized zones with higher porosities, and that the type and grade of karstification is facies-related.

The scale dependence of hydraulic conductivity is a critical issue in karst aquifer characterization. Medici and West (2021) reviewed this phenomenon across four UK karst aquifers and found that core-plug and slug tests are unsuitable because they do not characterize a large enough volume to include a representative fracture network. Hydraulic conductivity rises moving from the scale of core plug to slug and packer tests, which sample rock matrix and fractures, respectively (Medici & West, 2021). In the intensively karstified Carboniferous Limestone of the Mendips, the only hydraulic conductivity value found from spring recession was one order of magnitude higher than that indicated by pumping tests, due to dominance of flow through pipe-conduits (Medici & West, 2021). Noushabadi et al. (2011), as cited in Medici & West (2021), demonstrated that in Mesozoic fractured and karst aquifers of southern France, hydraulic conductivity rises by up to two orders of magnitude moving from the scale of pumping tests to pulse tests, with such high values related to karstification enlarging connective rock discontinuities.

The Role of the Epikarst Zone

The epikarst—the uppermost weathered zone of carbonate rocks—plays a critical role in controlling infiltration and the initial stages of groundwater circulation. Petrella et al. (2007) demonstrated the existence of an epikarstic zone approximately 10 m thick in a carbonate aquifer of southern Italy, where permeability is substantially greater than in the underlying rock mass due to fissuring and diffuse karstification. However, the hydrogeological behavior of the epikarst can vary significantly from classical conceptual models. At their test site, the contrast in permeability at the bottom of the epikarst did not cause retention of percolation or storage of water in a perched temporary aquifer; instead, the high fracture density and good interconnection of openings within the underlying limestone allowed diffuse percolation below the epikarstic zone (Petrella et al., 2007).

The formation and evolution of the epikarst is influenced by soil cover and CO₂ production. Celico et al. (2010) found that pyroclastic soil in the southern Apennines significantly influences epikarst formation, with a direct relationship between soil thickness and epikarst thickness. The sandy loam texture and high hydraulic conductivity of the soil allow easy rainwater infiltration, causing spatially homogeneous recharge within the aquifer system (Celico et al., 2010). The soil contains large accumulations of organic carbon, and considerable CO₂ production from microbial activity enhances the aggressiveness of infiltrating water toward carbonate dissolution (Celico et al., 2010).

In karst basins of southwest China, Zhang et al. (2011) demonstrated that the epikarst zone has large permeability near the surface due to CO₂-driven dissolution, offering fast water infiltration. As the extent and frequency of widening diminishes gradually with depth, epikarst permeability decreases (Zhang et al., 2011). This vertical gradient in permeability means that significant surface runoff is only generated after heavy rainfall events during the wet season, as most precipitation rapidly infiltrates through the epikarst (Zhang et al., 2011).

Structural Controls on Groundwater Circulation

Tectonic structures—faults, folds, and fracture systems—exert fundamental controls on groundwater circulation in karst aquifers by creating preferential flow paths or barriers to flow. Medici et al. (2021) reviewed how fractures in faulted stratigraphic successions are characterized by dominant sets of sub-vertical joints, and the maximum hydraulic conductivity and flow vectors are approximately sub-parallel to the preferential orientation of open fractures. The coupling between



groundwater flow direction and high flow rates in valleys explains the presence of karst conduits parallel to syncline axes (Medici et al., 2021).

Faults can exhibit complex dual behavior, acting simultaneously as conduits and barriers. Modeling carbonate faults with throws greater than approximately 100 m is particularly challenging because such faults are characterized by combined conduit-barrier behavior (Medici et al., 2021). The barrier behavior results from cataclastic deformation that reduces hydraulic conductivity perpendicular to the fault plane, while cavities can occur parallel to the strike of normal faults, generating channels for groundwater (Medici et al., 2021). In the Edwards Aquifer of Texas, faults play an important role in controlling groundwater flow: in some locations they restrict water flow where the Edwards Group is completely displaced and juxtaposed against less permeable units, while in others they provide pathways for water flow between karstified units (Schindel, 2019).

Petrella et al. (2014) provided experimental evidence of how low-permeability fault zones create compartmentalization in carbonate aquifers. Their study in southern Italy demonstrated that aquifer compartmentalization results from slight differences in permeability between lower-permeability fault zones and adjacent higher-permeability protoliths, with total head losses of approximately 80 m distributed across several aquitards (Petrella et al., 2014). This compartmentalization behavior differs from other carbonate environments where normal faults act as drains due to enhanced hydraulic conductivity (Petrella et al., 2014).

The structural complexity of karst aquifers is well illustrated by the Cassino plain in central Italy, where Saroli et al. (2019) demonstrated that thrust tectonics control the extent of hydrostructures and groundwater flow paths. Recharge is favored by numerous sinkholes, dolines, and karst depressions, while the carbonate slope complex, containing ribbon chert and siliceous layers, has slightly reduced permeability compared to pure limestone (Saroli et al., 2019). The regional aquitard consists of gray clays with very low permeability (Saroli et al., 2019).

At the Gran Sasso aquifer in central Italy, Medici et al. (2023) classified springs into structural geological groups determined by the position of permeability thresholds. The type of tectonic structures and the pattern of permeability thresholds correlate with computed discharge statistics (Medici et al., 2023). Joints and bedding plane fractures dominate groundwater flow, fitting both the relative steadiness of discharges and the pattern of Flow Duration Curves (Medici et al., 2023). The reduced dissolution in this aquifer is related to the combination of dolostones, relative abundance of marls, and dominance of highly layered limestones—rock types less prone to dissolution than massive limestones (Medici et al., 2023).

Flow Regimes and Groundwater Circulation Patterns

Karst aquifers exhibit a spectrum of flow regimes ranging from diffuse fracture flow to concentrated conduit flow, with most systems displaying a combination of both (Demiroglu, 2016; Filippini et al., 2018; Tamburini & Menichetti, 2020). Tamburini and Menichetti (2020) identified two types of aquifer behavior in the Umbria-Marche Apennine: unimodal aquifers with two hydrodynamic sub-regimes (fracture-controlled baseflow and conduit-controlled quickflow) and bimodal aquifers with only fracture network drainage. Their results indicate that the Maiolica Formation is characterized by high fracturation and slight karstification controlling infiltration and percolation, whereas the Calcare Massiccio Formation regulates deeper groundwater circulation through moderately developed conduit networks (Tamburini & Menichetti, 2020).

The hydrodynamic behavior of metamorphic karst aquifers in the Apuan Alps was investigated by Piccini et al. (2022), who found that marble karst aquifers are characterized by the predominance of conduit porosity over fissure and matrix porosities. This is explained by reduced interstitial porosity and fracturing of metamorphic carbonate rocks (Piccini et al., 2022). Spring monitoring revealed that piston flow is the common hydrodynamic response to infiltration, with strong dilution effects observed only during the heaviest rainfall events (Piccini et al., 2022). Water temperature and specific electrical conductivity increase only slightly during floods, indicating limited chemical and thermal exchanges between rock and stored water (Piccini et al., 2022).



Demiroglu (2016) classified karst springs in western Turkey based on hydrogeochemical responses, distinguishing between deep circulating waters (high electrical conductivity, high temperature, low dissolved oxygen) and shallow circulating waters (low EC, low T, high DO). Low variations in measurements between wet and dry seasons indicate fracture permeability predominantly controlled by diffuse groundwater flow, while high variations indicate conduit permeability with low storage but high transfer capability (Demiroglu, 2016).

The phenomenon of upwelling groundwater flow in karst areas was documented by Fiorillo et al. (2019), who demonstrated that karst aquifers can be characterized by high transmissivity and capacity to store large volumes of water, allowing deep-water circulation that generates ascendant flows in discharge zones where basal springs are located. Their numerical modeling using MODFLOW showed that a hydraulic conductivity of $K = 0.001$ m/s provided the best calibration results, consistent with values found in other karst areas of the Apennines (Fiorillo et al., 2019).

The residence time of karst groundwater varies enormously depending on the flow regime. Kilchmann et al. (2004) noted that the mean residence time of karst groundwaters ranges from a few hours to some months, as the largest proportion of groundwater flow occurs through conduits and fissures with only a small proportion transmitted through matrix porosity. However, Gil-Márquez et al. (2020) demonstrated that even small alpine karst systems can exhibit mean residence times of several decades, with old groundwater fractions ranging between 160 and 220 years in age, when the geological setting features highly tectonized media including units with diverse hydrogeological characteristics.

Influence of Karst on Regional Hydrogeological Frameworks

At the regional scale, karstification profoundly shapes the hydrogeological framework of carbonate aquifer systems. The Floridan Aquifer System provides a well-documented example: in west-central Florida, shallow groundwater circulation and high recharge rates contribute to large-scale dissolution of carbonate rocks along joints, fractures, and bedding planes (Williams & Kuniansky, 2015). Karst features such as submerged caves, large vugs, bedding plane voids, and vertical joints have been observed using borehole cameras and televiewers (Williams & Kuniansky, 2015). The vertical hydraulic conductivity of confining units ranges from 0.001 ft/d where thickness exceeds 100 ft to 0.05 ft/d in karst areas where thickness is less than 50 ft (Williams & Kuniansky, 2015).

In the Ozark Plateaus aquifer system, karst processes have enhanced a network of fractures and faults, creating marked permeability contrasts and aquifer anisotropy (Clark et al., 2019). The system is composed predominantly of fractured and dissolved carbonate rock, with relatively low groundwater storage values but high conductance through fractures and dissolution-enlarged conduits (Clark et al., 2019). The Ozark aquifer includes productive dolostone units with varying permeability characteristics depending on the degree of karstification and lithology (Clark et al., 2019).

Carter et al. (2021) demonstrated that in southern Ontario, the occurrence and movement of groundwater in shallow bedrock is principally controlled by modern karstic dissolution of subcropping carbonate and evaporite rocks, while in the intermediate to deep subsurface, paleokarst horizons developed during the Paleozoic control flow (Carter et al., 2021). Carbonate and evaporite rocks that form aquitards in the subsurface may form aquifers at or near the surface due to karstic dissolution by acidic meteoric water (Carter et al., 2021).

The Mediterranean region exemplifies the importance of karst aquifers at a continental scale. Xanke et al. (2024) documented that carbonate rocks cover approximately 39.5% of the Mediterranean region within a 250-km focus area from the coastline, with karst aquifers characterized by high degrees of hydraulic anisotropy, heterogeneity, and temporal variability. Mean annual karst groundwater loss from 2003 to 2020 was estimated at 436 million m^3 in this area (Xanke et al., 2024).

Modeling Approaches for Karst Aquifer Flow

The extreme heterogeneity of karst aquifers necessitates diverse modeling approaches. Medici et al. (2021) reviewed three principal approaches: equivalent porous medium (EPM), conduit network (CN), and discrete fracture network (DFN). Grid rotation is recommended when using EPM to match



higher hydraulic conductivity with the dominant orientation of joints (Medici et al., 2021). Cavities parallel to fault strikes require conduit network approaches that account for turbulence, and these conduits need to be embedded in an EPM due to smaller cavities present throughout the aquifer (Medici et al., 2021).

The MODFLOW-2005 conduit flow process (MODFLOW-CFP) represents a hybrid modeling approach that can simulate high transport velocities under laminar and non-laminar flow in karst conduit systems while accounting for the lower hydraulic conductivity rock matrix (Kuniansky et al., 2022). This is particularly important because the occurrence of turbulent flow is one of the identifying characteristics of karst aquifers (Kuniansky et al., 2022).

Medici et al. (2019) demonstrated the practical importance of modeling approach selection by showing that incorporation of fault conduits in a groundwater model strongly influences particle tracking results. Flow velocities ranging from ~100 to ~500 m/day were modeled in un-faulted areas, while karstic cavities in fault zones yielded velocities up to ~9000 m/day (Medici et al., 2019). Critically, effective porosities assumed for transport modeling in carbonate aquifers are typically two orders of magnitude higher than those found from tracer and hydrogeophysical tests, resulting in underestimated flow velocities (Medici et al., 2019; Medici & West, 2021).

Kozar and Weary (2009) demonstrated that equivalent-porous-medium approaches using MODFLOW can work well in karst settings when the locations of major conduit drains are known or can be accurately estimated. However, the approach requires careful parameterization, as the complex interplay between diffuse fracture flow and concentrated conduit flow cannot always be captured by a single modeling framework (Kozar & Weary, 2009; Medici et al., 2021).

Contaminant Transport Implications

The karst-modified permeability structure has profound implications for contaminant transport and aquifer vulnerability. Medici and West (2021) found that for all four UK carbonate aquifers studied, effective porosities assumed for transport modeling were two orders of magnitude higher than those found from tracer and hydrogeophysical tests, resulting in highly non-conservative estimates of aquifer vulnerability. They recommended effective porosity values in the range of 1%–0.01% for karst aquifers (Medici & West, 2021).

Rózkowski and Rózkowski (2016) characterized the unsaturated zone of a carbonate fissure-karstic aquifer in Poland, finding average surface fissure porosity of 0.12% for massive limestones and 0.45% for bedded limestones, with fissure permeability coefficients of 6.60×10^{-5} and 1.27×10^{-3} m/s, respectively. Tracer studies documented vertical migration rates from 8.1×10^{-6} to 4.9×10^{-5} m/s and lateral migration velocities between caves from 6.94×10^{-6} to 1.06×10^{-4} m/s (Rózkowski & Rózkowski, 2016).

Medici et al. (2021) applied the Transect Method to a dolomitic karst aquifer, demonstrating that the zone of maximum aquifer vulnerability is in the first 40 m below the soil surface, partially including the most conductive part of the aquifer ($K = 0.83$ – 2.89 m/day) in the depth interval 0–25 m below ground level. Enhancement of fracture hydraulic aperture in the first ~15 m below the water table, with computed apertures of 0.33–0.43 mm, drives the elevated near-surface hydraulic conductivity (Medici et al., 2021).

Sinkholes and karst conduits provide direct pathways for contaminants to enter carbonate aquifers (Frisbee et al., 2019; Kappel et al., 2020). The potential for focused recharge in karst is greatest where rocks crop out at or near the land surface and where closed depressions can focus infiltration of surface-water runoff into the aquifer (Kappel et al., 2020). Groundwater can flow quickly and over long distances through carbonate rock aquifers—for example, 9.5 km in just 25 hours in the Lost River karst basin of Indiana (Frisbee et al., 2019).

4. CONCLUSION

This review demonstrates that karstification is the dominant process controlling water circulation and permeability in carbonate aquifers, producing systems of extraordinary hydraulic



heterogeneity that challenge conventional hydrogeological approaches. Several key conclusions emerge from the synthesized literature:

- a. Karstification creates self-organized channel networks that fundamentally alter the permeability structure of carbonate rocks, producing hydraulic conductivities spanning up to eight orders of magnitude and groundwater velocities commonly exceeding 100 m/day. The degree of karstification is controlled by lithology (limestone versus dolostone), structural setting, and hydrodynamic conditions.
- b. The epikarst zone serves as a critical interface controlling infiltration and the initial redistribution of recharge water, with its development influenced by soil cover, CO₂ production, and the underlying fracture network. The vertical gradient in epikarst permeability has important implications for recharge dynamics and aquifer vulnerability.
- c. Tectonic structures exert fundamental controls on groundwater circulation, with faults exhibiting complex dual conduit-barrier behavior that creates aquifer compartmentalization and preferential flow paths. The interplay between structural geology and dissolution processes determines the spatial organization of karst drainage networks.
- d. Scale dependence of hydraulic parameters remains a critical challenge, with core-plug and slug tests systematically underestimating aquifer-scale hydraulic conductivity, and effective porosities used in transport models typically overestimated by two orders of magnitude. This leads to dangerous underestimation of contaminant transport velocities and aquifer vulnerability.
- e. Modeling karst aquifer flow requires integration of multiple approaches—EPM, DFN, and CN—to capture the full range of flow behaviors from diffuse matrix and fracture flow to turbulent conduit flow. No single modeling approach adequately represents the complete spectrum of karst hydraulic behavior.

Future research should focus on developing integrated multi-scale characterization frameworks that combine field observations, geophysical methods, and numerical modeling to better represent the spatial and temporal variability of karst aquifer properties. The increasing pressures of climate change and growing water demand make improved understanding of karst groundwater circulation essential for sustainable management of these critical water resources.

5. REFERENCES

- Bohnsack, D., Potten, M., Pfrang, D., Wolpert, P., & Zoßeder, K. (2020). Porosity–permeability Relationship Derived From Upper Jurassic Carbonate Rock Cores to Assess the Regional Hydraulic Matrix Properties of the Malm Reservoir in the South German Molasse Basin. *Geothermal Energy*. <https://doi.org/10.1186/s40517-020-00166-9>
- Carter, T. R., Fortner, L., J Russell, H. A., Skuce, M. E., Longstaffe, F. J., & Sun, S. (2021). A Hydrostratigraphic Framework for the Paleozoic Bedrock of Southern Ontario. *Geoscience Canada*. <https://doi.org/10.12789/geocanj.2021.48.172>
- Celico, F., Naclerio, G., Bucci, A., Nerone, V., Capuano, P., Carcione, M., Allocca, V., & Celico, P. (2010). Influence of Pyroclastic Soil on Epikarst Formation: A Test Study in Southern Italy. *Terra Nova*. <https://doi.org/10.1111/j.1365-3121.2009.00923.x>
- Clark, B. R., Duncan, L. L., & Knierim, K. J. (2019). *Groundwater Availability in the Ozark Plateaus Aquifer System*. <https://doi.org/10.3133/pp1854>
- Demiroglu, M. (2016). *Classification of Karst Springs for Flash Flood-Prone Areas in Western Turkey*. <https://doi.org/10.5194/nhess-2016-6>
- Fan, Y., Ji, H., Lu, R., Wan, J., & Huang, K. (2023). Control of Structural Landform Evolution on Karst Groundwater Cycle in a Large-Scale Anticlinorium. *Ground Water*. <https://doi.org/10.1111/gwat.13341>
- Filippini, M., Squarzone, G., Waele, J. D., Fiorucci, A., Vigna, B., Grillo, B., Riva, A., Rossetti, S., Zini, L., Casagrande, G., Stumpp, C., & Gargini, A. (2018). Differentiated Spring Behavior



- Under Changing Hydrological Conditions in an Alpine Karst Aquifer. *Journal of Hydrology*. <https://doi.org/10.1016/j.jhydrol.2017.11.040>
- Fiorillo, F., Leone, G., Pagnozzi, M., Catani, V., Testa, G., & Esposito, L. (2019). The Upwelling Groundwater Flow in the Karst Area of Grassano-Telese Springs (Southern Italy). *Water*. <https://doi.org/10.3390/w11050872>
- Frisbee, M. D., Meyers, Z. P., Miller, J., Gleason, C. L., Stewart-Maddox, N., Larson, E., Granger, D. E., Saksena, S., Dey, S., & Frisbee, E. (2019). Processes Leading to the Re-Activation of a Sinkhole in Buried Karst and the Subsequent Drying of Waterfalls in a Small Catchment Located in Northern Indiana, USA. *Journal of Cave and Karst Studies*. <https://doi.org/10.4311/2017es0116>
- Gil-Márquez, J. M., la Torre, B. D., Mudarra, M., Sültenfuß, J., & Andreo, B. (2020). Complementary Use of Dating and Hydrochemical Tools to Assess Mixing Processes Involving Centenarian Groundwater in a Geologically Complex Alpine Karst Aquifer. *Hydrological Processes*. <https://doi.org/10.1002/hyp.13848>
- Guardiola-Albert, C., Martos-Rosillo, S., Pardo-Igúzquiza, E., Durán Valsero, J. J., Pedrera, A., Jiménez-Gavilán, P., & Baena, C. L. (2014). Comparison of Recharge Estimation Methods During a Wet Period in a Karst Aquifer. *Ground Water*. <https://doi.org/10.1111/gwat.12310>
- Homuth, S., Götz, A. E., & Sass, I. (2014). Lithofacies and Depth Dependency of Thermo- And Petrophysical Rock Parameters of the Upper Jurassic Geothermal Carbonate Reservoirs of the Molasse Basin. *Zeitschrift Der Deutschen Gesellschaft Für Geowissenschaften*. <https://doi.org/10.1127/1860-1804/2014/0074>
- Kappel, W. M., Reddy, J. E., & Root, J. C. (2020). *Statewide Assessment of Karst Aquifers in New York With an Inventory of Closed-Depression and Focused-Recharge Features*. <https://doi.org/10.3133/sir20205030>
- Kilchmann, S., Waber, H. N., Parriaux, A., & Bensimon, M. (2004). Natural Tracers in Recent Groundwaters From Different Alpine Aquifers. *Hydrogeology Journal*. <https://doi.org/10.1007/s10040-004-0366-9>
- Kozar, M. D., & Weary, D. J. (2009). *Hydrogeology and Ground-Water Flow in the Opequon Creek Watershed Area, Virginia and West Virginia*. <https://doi.org/10.3133/sir20095153>
- Kuniansky, E. L., Taylor, C. J., Williams, J. H., & Paillet, F. (2022). *Introduction to Karst Aquifers*. <https://doi.org/10.21083/978-1-77470-040-2>
- Long, A. J., & Putnam, L. D. (2009). Age-Distribution Estimation for Karst Groundwater: Issues of Parameterization and Complexity in Inverse Modeling by Convolution. *Journal of Hydrology*. <https://doi.org/10.1016/j.jhydrol.2009.07.064>
- Medici, G., Lorenzi, V., Sbarbati, C., Manetta, M., & Petitta, M. (2023). Structural Classification, Discharge Statistics, and Recession Analysis From the Springs of the Gran Sasso (Italy) Carbonate Aquifer; Comparison With Selected Analogues Worldwide. *Sustainability*. <https://doi.org/10.3390/su151310125>
- Medici, G., Smeraglia, L., Torabi, A., & Botter, C. (2021). Review of Modeling Approaches to Groundwater Flow in Deformed Carbonate Aquifers. *Ground Water*. <https://doi.org/10.1111/gwat.13069>
- Medici, G., & West, L. J. (2021). Groundwater Flow Velocities in Karst Aquifers; Importance of Spatial Observation Scale and Hydraulic Testing for Contaminant Transport Prediction. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-021-14840-3>
- Medici, G., West, L. J., Chapman, P. J., & Banwart, S. A. (2019). Prediction of Contaminant Transport in Fractured Carbonate Aquifer Types: A Case Study of the Permian Magnesian Limestone Group (NE England, UK). *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-019-05525-z>



- Pavlič, K., & Parlov, J. (2019). Cross-Correlation and Cross-Spectral Analysis of the Hydrographs in the Northern Part of the Dinaric Karst of Croatia. *Geosciences*. <https://doi.org/10.3390/geosciences9020086>
- Petrella, E., Aquino, D., Fiorillo, F., & Celico, F. (2014). The Effect of Low-permeability Fault Zones on Groundwater Flow in a Compartmentalized System. Experimental Evidence From a Carbonate Aquifer (Southern Italy). *Hydrological Processes*. <https://doi.org/10.1002/hyp.10294>
- Petrella, E., Capuano, P., & Celico, F. (2007). Unusual Behaviour of Epikarst in the Acqua Dei Faggi Carbonate Aquifer (Southern Italy). *Terra Nova*. <https://doi.org/10.1111/j.1365-3121.2006.00720.x>
- Piccini, L., Nannoni, A., & Poggetti, E. (2022). Hydrodynamics of Karst Aquifers in Metamorphic Carbonate Rocks: Results From Spring Monitoring in the Apuan Alps (Tuscany, Italy). *Hydrogeology Journal*. <https://doi.org/10.1007/s10040-022-02569-3>
- Różkowski, J., & Różkowski, K. (2016). Influence of Fissuring and Karstification of the Carbonate Aquifer Unsaturated Zone on Its Vulnerability to Contamination (Cracow Upper Jurassic Region, Poland). *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-016-5790-3>
- Saroli, M., Lancia, M., & Petitta, M. (2019). The Geology and Hydrogeology of the Cassino Plain (Central Apennines, Italy): Redefining the Regional Groundwater Balance. *Hydrogeology Journal*. <https://doi.org/10.1007/s10040-019-01953-w>
- Schindel, G. M. (2019). *Genesis of the Edwards (Balcones Fault Zone) Aquifer*. [https://doi.org/10.1130/2019.1215\(02\)](https://doi.org/10.1130/2019.1215(02))
- Tamburini, A., & Menichetti, M. (2020). Groundwater Circulation in Fractured and Karstic Aquifers of the Umbria-Marche Apennine. *Water*. <https://doi.org/10.3390/w12041039>
- Williams, L. J., & Kuniansky, E. L. (2015). *Revised Hydrogeologic Framework of the Floridan Aquifer System in Florida and Parts of Georgia, Alabama, and South Carolina*. <https://doi.org/10.3133/pp1807>
- Worthington, S. R. H., & Ford, D. (2009). Self-Organized Permeability in Carbonate Aquifers. *Ground Water*. <https://doi.org/10.1111/j.1745-6584.2009.00551.x>
- Xanke, J., Goldscheider, N., Bakalowicz, M., Barberá, J. A., Broda, S., Chen, Z., Ghanmi, M., Günther, A., Hartmann, A., Jourde, H., Liesch, T., Mudarra, M., Petitta, M., Ravbar, N., & Stevanović, Z. (2024). Carbonate Rocks and Karst Water Resources in the Mediterranean Region. *Hydrogeology Journal*. <https://doi.org/10.1007/s10040-024-02810-1>
- Zhang, Z., Chen, X., Ghadouani, A., & Shi, P. (2011). Modelling Hydrological Processes Influenced by Soil, Rock and Vegetation in a Small Karst Basin of Southwest China. *Hydrological Processes*. <https://doi.org/10.1002/hyp.8022>